

Soil Aggregate Abrasion by Impacting Sand and Soil Particles

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ABSTRACT

DURING wind erosion, erodible particles (< 0.85 mm diameter) are removed continually in saltation and suspension, but the supply of particles is rarely exhausted because new erodible-size particles are created constantly by abrasion. Little is known about the physics of soil abrasion, however. This study was undertaken to determine the effects of particle speed, size, impact angle, and stability on the abrasive erosion (W) of soil aggregates of various stabilities. A calibrated sandblasting device was used to abrade individual aggregates with weighed amounts of abrader in an enclosed chamber and the weight of soil abraded from the aggregates was determined. Regression equations relating aggregate abrasion to the experimental variables were then developed.

Sand abrader produced higher values of W than soil abrader. W also increased as a power of particle velocity. The power was near 2.0 for fragile aggregates and ranged from 1.5 to 2.3 for the most stable aggregates tested. The W of all aggregates decreased nonlinearly as aggregate stability increased. The largest W occurred at impact angles of 20 to 30 deg, and a small increase in W occurred as average particle diameter increased from 125 to 715 μm .

INTRODUCTION

The wind erosion equation (Woodruff and Siddoway, 1965) is the primary tool used to predict wind erosion and to design wind erosion control practices. Currently, the percentage of surface soil aggregates > 0.84 mm diameter is used in the equation as a measure of field erodibility. This measure indicates roughly the soil fraction that is readily available for wind erosion and the soil fraction that will resist erosion. However, this measure tells us little about the likely rates of abrasive breakdown once erosion begins. Yet on large, cloddy fields, abrasive breakdown is the source of most of the soil lost. For example, on a smooth field with 50% of the aggregates > 0.84 mm, the wind erosion equation predicts a loss $< 2.0 \text{ T ha}^{-1}\text{yr}^{-1}$ on a narrow field with little abrasion, but predicts a loss of $85 \text{ T ha}^{-1}\text{yr}^{-1}$ on a wide field of the same cloddiness at Garden City, Kansas. In order to improve our ability to predict field erodibility, we must gain a better understanding of the influence of various factors on the abrasive breakdown of

soil aggregates. The objective of this study was to determine the influence of particle velocity, size, impact angle, and stability on the abrasive erosion of soil aggregates.

REVIEW OF LITERATURE

There has been little careful experimentation on the abrasive erosion of soil aggregates and most of the information on abrasion has been developed from tests on homogeneous, brittle materials. In his book "Crushing and Grinding," Lowrison (1974) stated "abrasion cannot generally be defined and it is necessary to use clearly defined tests which allow results on the same material to be reproduced; clearly, the closer these tests are to the circumstances in which abrasion is to be predicted, the better."

Abrasive erosion (W) is usually reported as mass of material removed from the target per unit mass of impinging particles. We will first review how individual variables affect abrasive erosion as shown by experiments and then consider possible theoretical approaches to the problem.

For a given target and abrader (p), abrasive erosion is often described as

$$W = f(V_p^c, d_p^b, \alpha) \dots\dots\dots [1]$$

where V_p is particle velocity, d_p is particle diameter, α is angle of impact, and c and b are constants.

In a review of the literature, Preece and Macmillan (1977) found that the exponent " c " ranged from 2.0 to 6.5. Chepil (1958) suggested that in soil abrasion the exponent should be 2. In early tests, Chepil (1946) blew an abrader at target soil cylinders on the wind tunnel floor. If we assume that particle speeds were proportional to the reported windspeeds, then Chepil's data show " c " varying from 0.88 to 6.24. Later, Chepil (1951) placed trays of clods on the wind tunnel floor and blew an abrader over them. In these tests, W usually decreased as velocity increased, thus making " c " negative in most cases. The latter results suggest that variations in length of jump and lateral distribution of the saltating particles occur in the tunnel, so that an independent measurement of " c " there would be difficult.

Most experimental observations are at $V_p \gg$ those occurring in wind erosion, although many of the same phenomena likely occur. For example, Tilly and Sage (1970) observed that there was a minimum size and speed combination at which abrasion began. When the small particles didn't break, the exponent " c " was near 2 and they concluded that fragmentation caused additional abrasion. Preece and Macmillan (1977)

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suggested that the reason for the decrease in W with particle size is that the effective flow stress of the material increases as the stressed volume decreases (i.e., the probability of a flaw in the stressed volume is less).

In reviewing the data on brittle materials, Engel (1976) concluded that W is maximum when α is near 90 deg. One would expect soil aggregates to behave like brittle materials, but there are no data on soils to verify this hypothesis. Data of Tilly and Sage (1970) show that soft particles cause larger W at $\alpha = 90$ deg than do hard particles. The increase in W may be caused by fragmentation. They also found that there was a linear relationship between quartz content and W caused by soil particles abrading compressor blades.

In considering various targets, Preece and Macmillan (1977) stated that there was no simple procedure to establish the solid particle resistance of a target. However, we know that in soils, abrasion resistance varies widely. Chepil (1958) reported that abrasion resistance varied directly with mechanical stability as measured by sieving. Unfortunately, sieving is not a very sensitive indicator of abrasion resistance; in Chepil's data, the mechanical stability of aggregates decreased about 5 percent for a fivefold increase in the abrasion rate. Chepil (1951) also found that abrasion resistance varied directly with fineness of soil texture.

Engel (1976) has reported a theoretical solution to the brittle abrasion problem. In its simplest approximate form for spheres, the result was:

$$W \propto \frac{E^{0.8}}{\delta_b^2} R^{3\mu/\mu-2} V_p^{2.4\mu/\mu-2} \dots \dots \dots [2]$$

where E is modulus of elasticity, δ_b is fracture stress in bending, R is particle radius, V_p is particle velocity, and μ is the flaw distribution parameter. Because of the difficulty in determining the parameters, this approach to calculating W appears more difficult than measuring W directly for soil aggregates.

A second approach has been to use dimensional analyses on all the possible variables and then form dimensionless π -terms. Finally, regression analyses were applied to the data to determine the significance of the various π -terms.

Another approach has been to apply regression analyses directly to the independent variables to form prediction equations for W . Because of the analytical difficulties posed by nonhomogeneous materials, the latter two approaches have been most successful.

EXPERIMENTAL PROCEDURES

Soil samples of Haynie very fine sandy loam, Keith silt loam, and Wymore silty clay loam were collected from the surface of tilled fields and air-dried. The soil samples were then rotary sieved to separate the fractions to be used as targets and abradant. Local quartz, river sand was also washed and sieved for use as an abrading material. The three sieved size fractions used for abradant were 100 to 150, 290 to 420, and 590 to 840 μm in diameter. The target aggregates were generally larger than 4 cm in diameter, and one side was leveled with a knife to use for the impaction surface.

A commercial sandblasting nozzle was used to fire the particles at the target aggregates. Average particle velocity was determined by calibrating the nozzle using a modification of a method suggested by Ruff and Ives

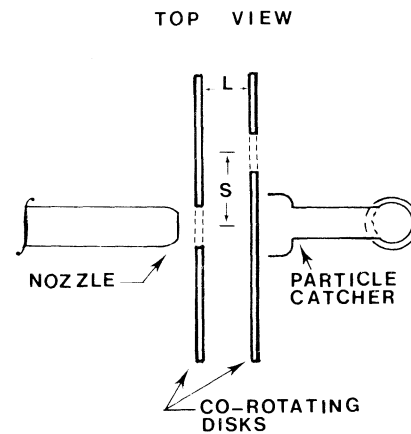


Fig. 1—Schematic diagram of apparatus used to determine particle velocity as a function of nozzle air pressure.

(1975) and the apparatus illustrated in Fig. 1. The nozzle was positioned at a radius R from the center of two co-rotating disks. The disks were rotated at an angular velocity ν , spaced a distance L apart, and each had a narrow slot offset from the other an arc length S . The ν at which the maximum number of particles were caught after passing both slots corresponded to the average particle velocity (V_p) between the disks and was calculated from the equation

$$V_p = R\nu L/S \dots \dots \dots [3]$$

To maintain constant particle velocity during each calibration and abrasion test, a pressure regulator was used to provide constant air pressure to the nozzle and a vibratory feeder was used to provide a constant feed rate of 1.67 g/s of abradant. Wolak et al. (1977) have measured particle velocity as a function of radial position within a nozzle jet and found that particle velocity at the jet periphery was about 92% of the centerline particle velocity. Thus, particle velocity within the jet may be rather uniform.

In this study, four impact velocities (V_p) were used for each abradant size. The various V_p were obtained by varying the air pressure, and they ranged from 4.0 to 12.0 m/s for the smallest particles to 3.0 to 9.0 m/s for the largest particles. These ranges of V_p would likely also occur in wind erosion events. Individual target aggregates were abraded with weighed amounts of abradant until about 2 to 6 g of soil was abraded from their surface. The soil abradant was always of the same texture as the target aggregate, while the sand abradant was used on targets of all textures. Three impact angles (α) of 15, 30, and 90 deg were obtained by changing the angle of the nozzle relative to the impact surface of the target.

After abrasion, each target aggregate was subjected to a drop test similar to that described by Farrell et al. (1967). The aggregates were dropped inside a tube onto a concrete floor from a height of 2 or 3 m and the resultant particle size distribution determined by sieving. Energy input to the aggregate was calculated from the drop height. New surface area created by the drop was calculated from the size distribution, assuming that the particles were spherical. The ratio of energy input to new surface area created was used as a measure of aggregate

stability (S_a).

Samples of the soil abrader also were impacted on a steel plate mounted inside a particle sizing apparatus. New surface area created by the impact and kinetic energy at impact were calculated and ratios determined in a manner similar to the aggregate tests to provide a measure of soil particle stability (S_p).

The data were analyzed using multiple regression on the following primary variables:

$$W = f(\alpha, d_p, V_p, S_a) \dots \dots \dots [4]$$

where α is angle of abrader impact in degrees, d_p is average particle diameter in μm , V_p is average particle impact velocity in cm/s , S_a is aggregate stability in J/m^2 , and W is abrasive erosion in g/kg . Secondary variables constructed from the primary variables and their interactions also were added to the data set. In the analyses, there were 223 observations of aggregate abrasion using soil as the abrader and 296 observations using sand as the abrader.

RESULTS AND DISCUSSION

A number of multiple linear regression models were considered in the data analyses, and a transformation using natural logarithms was finally selected. For soil abrader, the best 7-variable model found using a stepwise regression procedure was

$$\begin{aligned} \ln W = & -7.84835 + (2.0568 + 0.00156 S_a^2 \\ & -0.0000333 \alpha^2) \ln V_p + (-1.3557 + 0.0004612 d_p \\ & + 0.011784 \alpha) \ln S_a - (0.067573 S_a) \ln \alpha. \dots \dots [5] \end{aligned}$$

The coefficient of multiple determination (R^2) for this model was 0.78. All the independent variables were significant at the 0.01 or 0.02 level (Table 1). For sand abrader, the best 7-variable model was

TABLE 1. ANALYSIS OF VARIANCE, STANDARD ERRORS OF THE VARIABLE COEFFICIENTS, AND PARTIAL F'S FOR SOIL ABRADER MODEL.

Source	Degrees of freedom	Mean square	Overall F
Regression	7	45.72	109.0†
Error	215	0.4195	
Total	222		

Variable	Standard error	Partial F
$\ln V_p$	0.118987	289.8†
$S_a^2 (\ln V_p)$	0.000475	10.8†
$\alpha^2 (\ln V_p)$	0.000003	107.4†
$\ln S_a$	0.183242	54.7†
$d_p (\ln S_a)$	0.000159	8.3†
$\alpha (\ln S_a)$	0.003017	15.3†
$S_a (\ln \alpha)$	0.028650	5.56*

*Significant at 0.02 level.

†Significant at 0.01 level.

TABLE 2. ANALYSIS OF VARIANCE, STANDARD ERRORS OF THE VARIABLE COEFFICIENTS, AND PARTIAL F'S FOR SAND ABRADER MODEL.

Source	Degrees of freedom	Mean square	Overall F
Regression	7	82.859	252.5†
Error	288	0.3281	
Total	295		

Variable	Standard error	Partial F
$\ln V_p$	0.102648	365.9†
$S_a (\ln V_p)$	0.010581	11.3†
$\alpha (\ln V_p)$	0.000274	8.8†
$\ln S_a$	0.161456	8.8†
$d_p (\ln S_a)$	0.000117	8.0†
$\alpha^2 (\ln S_a)$	0.000013	143.6†
$S_a^2 (\ln \alpha)$	0.000784	15.2†

†Significant at 0.01 level.

$$\begin{aligned} \ln W = & -7.7424 + (1.9636 - 0.3555 S_a \\ & + 0.000811 \alpha) \ln V_p + (-0.478857 + 0.000329 d_p \\ & - 0.000156 \alpha^2) \ln S_a + (0.003054 S_a^2) \ln \alpha. \dots \dots [6] \end{aligned}$$

The R^2 for this model was 0.86. Again, all the independent variables were significant at 0.01 level (Table 2). Computer plots of the residuals of both models were examined and appeared to have a satisfactory behavior.

The data were analyzed in two groups based on the type of abrader, because soil and sand particles behave differently on impact. For example, fine sandy loam soil particles impacted at 90° on a steel plate exhibited an S_p directly proportional to V_p and inversely proportional to d_p (Fig. 2). This complex behavior of S_p needs further investigation and could probably be used to reduce some of the unexplained variance in equation [5]. In contrast, Lowrison (1974) reported primary sand particles had an S_p of 894 J/m^2 and thus would not break down significantly for the V_p used in this study. In general, the sand abrader produced larger W than the soil abrader,

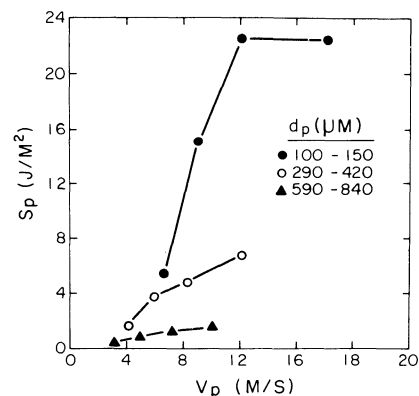


Fig. 2—Effect of particle velocity (V_p) and diameter (d_p) on particle stability (S_p) of very fine sandy loam soil.

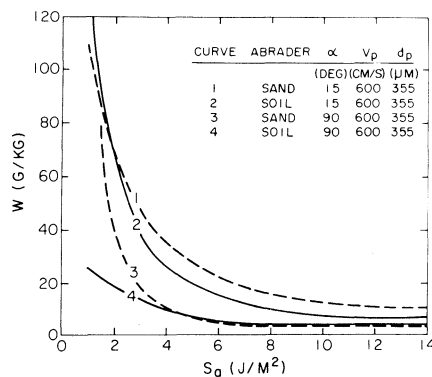


Fig. 3—Predicted aggregate abrasive erosion (W) as a function of aggregate stability (S_a).

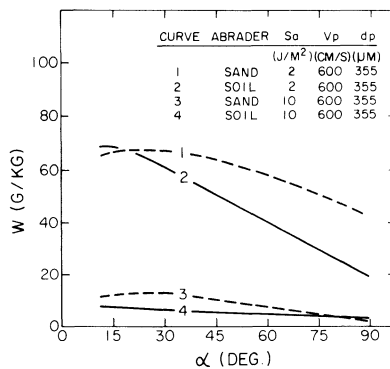


Fig. 4—Predicted aggregate abrasive erosion (W) as a function of impact angle (α).

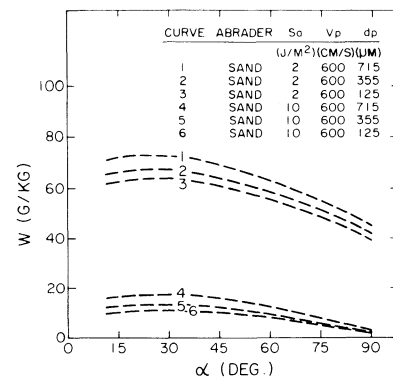


Fig. 5—Predicted aggregate abrasive erosion (W) as a function of impact angle (α) for three diameters (d_p) of sand abradant.

but on sandy soils, repeated impacts may cause the particles to become like the sand abradant and increase W.

To illustrate the effect of various independent variables on the dependent variable W, several plots of predicted results were made. Fig. 3 shows that as S_a increased from about 1 to 6 J/m^2 , there was a sharp drop in W, while beyond 6, W decreased slowly. Fragile, fine sandy loam aggregates with S_a of 0.5 J/m^2 could be found in the field, but after a single rotary sieving, only aggregates with S_a about 0.75 J/m^2 or more survived. However, the aggregates that survive sieving can possess a wide range of W, as shown in Fig. 3. Thus, there is a need for a simple, sensitive test for dry aggregate stability (or other property), which is highly correlated to W. Whether the drop test used here, the crushing index proposed by Skidmore and Powers (1982), or some other test should be selected is a subject of continuing research at our laboratory.

The effect of α on W is illustrated in Fig. 4. The largest W occurred at 30 deg for the sand abradant and 15 deg for the soil abradant. Because the nozzle produced too large an impact area, α 's of less than 15 deg were not tested. Tests on materials other than soil always show W decreasing as α approaches zero, however (Engel, 1976). The effect of α on W of the aggregates was unexpected because brittle materials usually exhibit the largest W at α of about 90 deg. In recent abrasion tests of rocks and other materials, Greeley et al. (1982) also found that natural materials often exhibit surprising combinations of brittle and ductile behavior. The results in Fig. 4 suggest that rough or ridged surfaces that promote large α may be more resistant to abrasion than smooth surfaces, particularly if the surface aggregates are fragile.

As d_p increased, so did W for the aggregates; however, d_p had less effect on W than α , S_a , or V_p (Fig. 5). There are two possible mechanisms that could cause W to increase with d_p . First, as d_p increased, the likelihood of the impact area containing a weak or flawed area also increased. Second, as d_p increased, the maximum impact stress during each impact also increased, as described by Engel (1976).

The literature review indicated a wide variation for the exponent c in the equation

$$W \propto V_p^c \quad [7]$$

For the conditions in this study, c ranged from about 1.5 to 2.3 (Fig. 6). For fragile clods and sand abradant, $c \approx 2$,

but decreased as S_a increased. Evidently, as S_a increased, a larger fraction of the impact kinetic energy went to deformation instead of breakdown of the aggregate. In the case of soil abradant, c increased as S_a increased. This was probably the result of secondary erosion caused by fragmentation of the impacting soil particles.

SUMMARY AND CONCLUSIONS

During wind erosion, abrasive erosion (W) of soil aggregates is often a major source of erodible-size particles, but little is known about the physics of soil aggregate abrasion. The objective of this study was to determine the effects of particle velocity (V_p), size (d_p), impact angle (α), and stability (S_p) on the W of soil aggregates of various stabilities (S_a). A calibrated sand-blasting device was used to abrade individual aggregates with weighed amounts of abradant in an enclosed chamber and the weight of soil abraded from each aggregate was determined. Soil of the same texture as the individual aggregate and sand were used as the two abraders on aggregates of very fine sandy loam, silt loam, and silty clay loam.

Regression equations for both sand and soil abradant relating W to S_a , V_p , d_p , and α were developed. Sand abradant produced higher values of W than soil abradant because sand had the highest S_p . W also increased as a power of V_p . The power was near 2.0 for fragile aggregates and ranged from 1.5 to 2.3 for the most stable aggregates tested. The W of aggregates of all textures decreased in a non-linear fashion as S_a increased. In general, increasing S_a from 1 to 14 J/m^2 decreased W by

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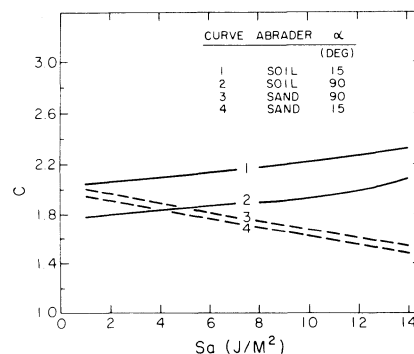


Fig. 6—Predicted variation in exponent of particle velocity (c) as a function of aggregate stability (S_a).

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at least a factor of 10. The aggregate response to α was unexpected in that the aggregates behaved somewhat like ductile materials and had the largest W at α of 15 to 30 deg. Finally, a small increase in W occurred as average d_p increased from 125 to 715 μm .

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